

## Nitrous Oxide Ethanol Bi-propellant Rocket Engine & Gas Generator Development and Testing

Mark C. Grubelich<sup>\*</sup>, Stewart H. Youngblood<sup>†</sup>, Michael J. Hargather<sup>‡</sup>, and Venner Saul<sup>§</sup>

### Abstract

A 150 lb<sub>f</sub> thrust class, modular, bi-propellant, rocket engine/gas-generator and supporting test infrastructure has been developed in a cooperative effort between Sandia National Laboratories and the New Mexico Institute of Mining and Technology's (NMIMT's) Energetic Materials Research and Testing Center (EMRTC). This modular test engine design consists of a head end fuel-oxidizer injector, a spark ignition gaseous H<sub>2</sub>/O<sub>2</sub> torch igniter, combustion chamber and nozzle module. This robust design allows for rapid configuration changes as well as economical repair should hardware become damaged in testing. The engine interfaces with a permanently installed pressurizing system capable of delivering liquid nitrous oxide and a variety of liquid fuels for both rocket engine development and propellant performance evaluation. The regulated high pressure systems allows for delivery of liquefied gases above their saturation pressure as well as allowing for high pressure rocket engine/gas-generator operation. The facility test cell houses a 1 ton thrust capacity test stand leaving room for larger scale engine development.

Initial testing of the modular bi-propellant rocket engine involved evaluation of nitrous oxide and ethanol as potential "green" rocket propellants. Thrust and pressure measurements along with high-speed digital imaging of the rocket engine exhaust plume were conducted. Prompt starting without pressure oscillation or instability was demonstrated. Nitrous oxide and ethanol were shown to perform well as rocket propellants, with specific impulses experimentally measured in the range of 250 to 265 lb<sub>f</sub>-sec/lb<sub>m</sub> at ground level operating conditions. This paper will discuss the design, development and fabrication of the test facility and the modular bi-propellant rocket engine/gas-generator as well as potential applications. Future testing plans will be discussed.

### Introduction

The advancements in space exploration have expanded the need for methods to improve current and develop new propulsion technologies. For liquid fueled rocket engines, this includes the development of propellants and rocket engine designs. To develop new propulsion technologies, especially rocket propellants, significant testing is necessary to establish the viability of concepts and develop reliable system designs. Small scale laboratory testing is vital, as large scale testing is expensive and challenging with new or unproven propulsion technologies. Small scale laboratory testing is best supported by dedicated test facilities with hardened infrastructure to safely and economically explore the performance ranges of new propulsion technologies, including those with probabilities of failures.

---

<sup>\*</sup> Distinguished Member of the Technical Staff, Sandia National Laboratories, New Mexico, 87123. Contact: mcgrube@sandia.gov

<sup>†</sup> Former Graduate Research Assistant, Department of Mechanical Engineering, New Mexico Tech, 801 Leroy Place, Socorro, New Mexico, 87801. Contact: stewarty@nmt.edu

<sup>‡</sup> Assistant Professor, Department of Mechanical Engineering, New Mexico Tech, 801 Leroy Place, Socorro, New Mexico, 87801. Contact: mjh@nmt.edu

<sup>§</sup> Principal Member of the Technical Staff, Sandia National Laboratories, New Mexico, 87123. Contact: wvsaul@sandia.gov

New test facility development, especially at universities, is important to respond to changing needs for propulsion systems and to train the next generation of propulsion engineers. Through a cooperative effort between Sandia National Laboratories and the New Mexico Institute of Mining and Technology's (NMIMT, New Mexico Tech) Energetic Materials Research and Testing Center (EMRTC), a hardened test facility was designed and constructed to support testing of novel liquid propellant combinations and rocket engine designs. The facility was designed to allow quick changes to support testing and provide data collection for a variety of propellants and rocket engine designs, while being simple enough to allow direct usage by undergraduate and graduate engineering students for coursework and research. The facility has an operational nitrous oxide and ethanol bi-propellant rocket engine developed in house that is the basis for operational envelope testing.

### **Background**

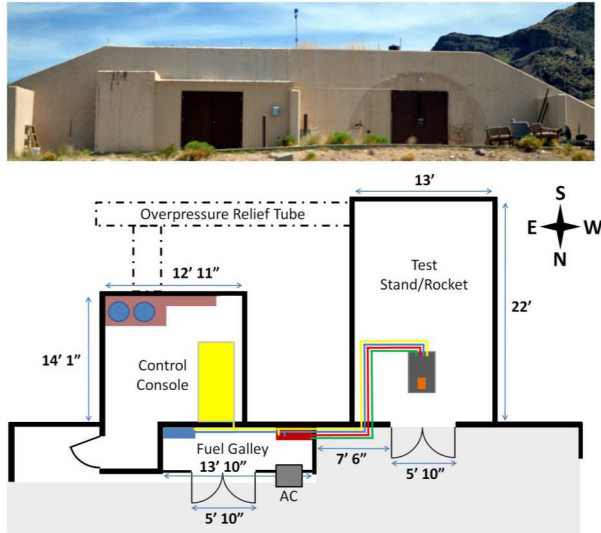
Research efforts have focused on the use of nitrous oxide and ethanol as rocket engine propellants, from both a performance and safety standpoint [1,2]. Ethanol is a clean burning and renewable fuel with high potential as a next generation fuel [2]. Nitrous oxide has potential as an oxidizer for use in both hybrid and liquid bi-propellant rocket engines [3, 4], and can be simpler to handle than cryogenic liquid oxygen. Research at Stanford University has successfully implemented nitrous oxide with hybrid rocket engines [4]. In Japan, a bi-propellant rocket engine using ethanol and nitrous oxide was successfully demonstrated by Tokudome et al. with a thrust of 2kN (225lbs) and a vacuum specific impulse of 294 seconds [5]. Clearly, nitrous oxide has potential as a rocket propellant oxidizer.

Development of new testing facilities can be difficult from a safety and environmental standpoint, but research papers have described laboratory-scale facilities supported by both corporate and government interests. Peretz et al. [6] from Israel has built a hybrid rocket motor testing facility, and academic groups from Purdue [7] and Stanford University [8] operate laboratory scale test facilities for a range of rocket engine testing applications. The High Pressure Laboratory at the Maurice Zucrow Laboratories at Purdue University is one of the most active academic-scale rocket engine test facilities in the USA. The facility was designed for testing new and novel technologies with a hardened infrastructure [7], and serves as a model for the facility developed at NMIMT.

### **Test Facility**

The current test facility, referred to as the Rocket Engine Facility (REF), was developed through collaboration between Sandia National Laboratories and NMIMT. The facility was constructed within the EMRTC field laboratory in a former explosive manufacturing facility. EMRTC is a research division of NMIMT, located in Socorro, NM, adjacent to the main campus. The structure that comprises the REF was originally designed for explosive operations with up to 498kgs (1100lbs) of TNT equivalence. With the estimated TNT equivalence of all propellants on-site of 66.2kgs (146lbs) of TNT, a significant safety margin is provided with room for future expansion to larger rocket engine testing [9].

The floor plan of the facility permits isolation of the propellant feed system from the test engine; this eliminates a cascading failure case from destroying the entire test apparatus. This is ideal for testing novel engine designs and propellant combinations where failure may be a common occurrence. The installed rocket engine mounting hardware is capable of supporting test firing of rocket engines of up to 8896N (2000lbf) thrust. Figure 1 shows the layout of the REF, including the separation of the propellant supply system from the rocket engine test cell.



*Figure 1: Rocket Engine Facility Layout*

The fuel galley consists of three reinforced concrete walls on the West, East, and South sides. The North side is a blowout wall designed to fail under over-pressure conditions. This allows any energetic event that may occur inside of the fuel galley to be directed away from the facility, limiting damage to personal and hardware. The fuel galley is temperature conditioned to allow year round operations.

The rocket engine is housed in a test cell originally utilized for the explosive manufacturing operations. The test cell is also constructed with a blowout wall at the North end for over-pressure relief. The test cell can be sealed to protect all equipment and instrumentation from weather and allowing precision optical instruments to be used for tests performed over long periods of time. During test firing of the rocket engine the North wall are opened. The current engine nozzle exit plane is recessed inside the test allowing for optical diagnostics of the exhaust plume that subsequently exists to the outlying countryside.

The operators and control systems are housed in the facility's control room. The close proximity of the control room to the test cell permits rapid changes to be made in the fuel galley as well as modification to the rocket engine configuration. Data acquisition and control lines are routed from the control room directly to the fuel galley and test cell through dedicated passages in the reinforced concrete walls.

### **Rocket Engine Design**

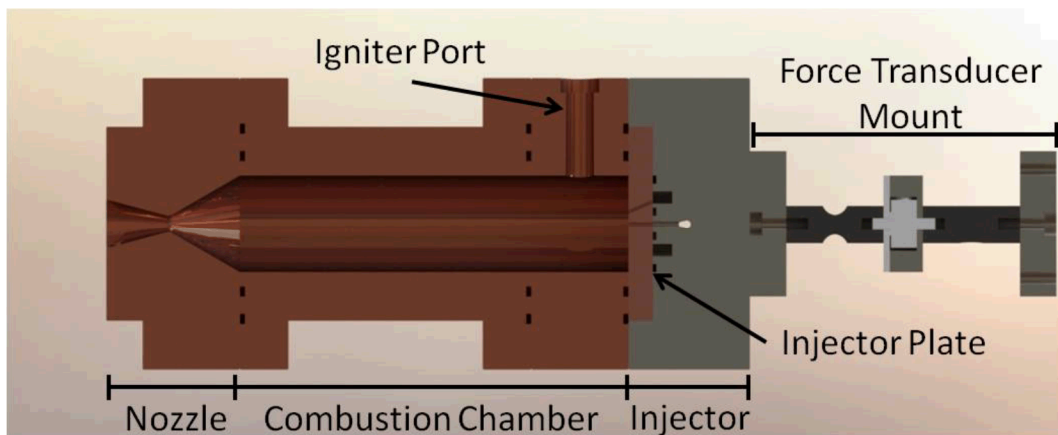
Three design principles were adhered to during the development of the rocket engine housed at REF:

1. *Robust* for increased safety and survivability of the engine.
2. *Modular* design to provide increased versatility and ease for future modifications and repairs.
3. *Simple* to decrease operational down time by using commercial off the shelf, easily replaceable parts where possible and simple machining methods for custom manufactured parts.

The intended use of the rocket engine was to experimentally evaluate the performance of nitrous oxide and ethanol as liquid propellants across a range of operating conditions, while providing an academic opportunity for training undergraduate and graduate students in rocket propulsion

experimental techniques and analysis. The rocket engine was also designed to allow development of optical diagnostics techniques to be developed for exhaust plume research.

The rocket engine was designed for a nominal chamber pressure of 6.89MPa (1000psi) and approximate thrust of 667N (150lbf)[9]. A conical 15 degree half angle exhaust nozzle design was chosen for simplicity in fabrication and designed for optimal expansion (Mach 3 flow condition). The rocket engine has a characteristic length,  $L^*$ , of 7.33m (288.6 inches)[9]. The rocket engine was designed to be passively heat sink cooled via the mass of the rocket engine and allows for 10 second run times. The combustion chamber and nozzle were fabricated from oxygen-free, high conductivity (OFHC) copper. Sealing between sections was accomplished by fluorocarbon elastomer O-rings which have demonstrated multi-fire use without degradation or loss of sealing ability [9]. Typical post fire equilibrium temperature of the engine is 533K (500 °F). Figure 2 is a cross-sectional view of the assembled engine, and shows the dual O-rings seals at the flange interface, the igniter-engine interface port, the force transducer mounting assembly, and the injector plate and injector assembly.



*Figure 2: CAD cutaway of assembled rocket engine. Main components are labeled.*

Propellant flow rates are controlled by cavitating venturis; this allows the propellant flow rates to be only a function of the upstream nitrogen supply pressure [10]; this decouples the propellant feed system from combustion chamber pressure fluctuations. The propellants flow into the engine through a simple impinging jet injector plate as discussed by Sutton[12]. Three fuel ports surround a single central oxidizer port, each with a 24° relative angle to the oxidizer port. The interchangeable injector plates permit different injector configurations to be interchanged as needed. Ignition of the propellants is accomplished by a gaseous hydrogen-oxygen torch based on a design Repas[11]. Figure 3 shows the assembled rocket engine.

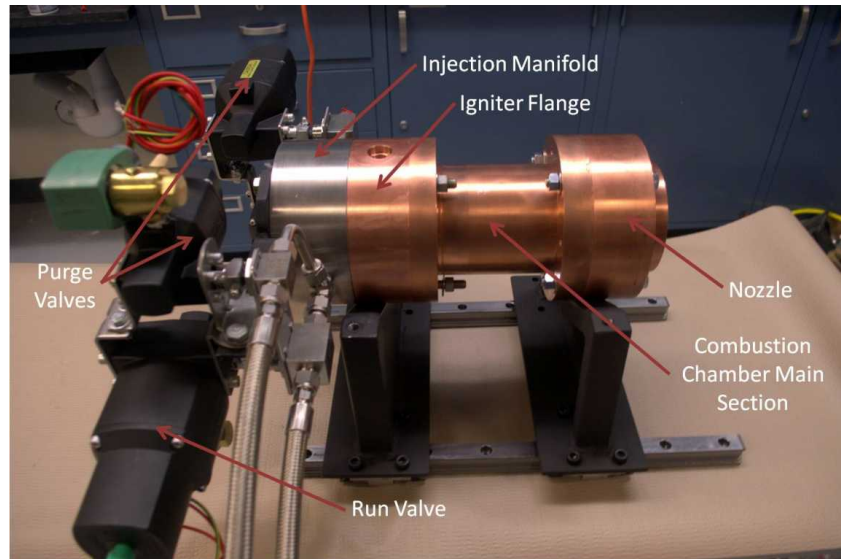


Figure 3: Assembled rocket engine prior to installation in test facility

### Propellant Supply System

A constant pressure system is used for supplying propellants to the rocket engine. This system uses nitrogen gas to push propellant from storage tanks through feed lines to the rocket engine. Liquid propellants are supplied to the engine from bottom tank outlets while maintaining the tank pressures above the saturation pressure of the propellant. Figure 4 is a simplified schematic of the propellant supply system. The system is designed to isolate the fuel and oxidizer, with each system having its own nitrogen supply and purge system. In the schematic, green represents the oxidizer, red represents the fuel, and blue represents the nitrogen push and purge gases.

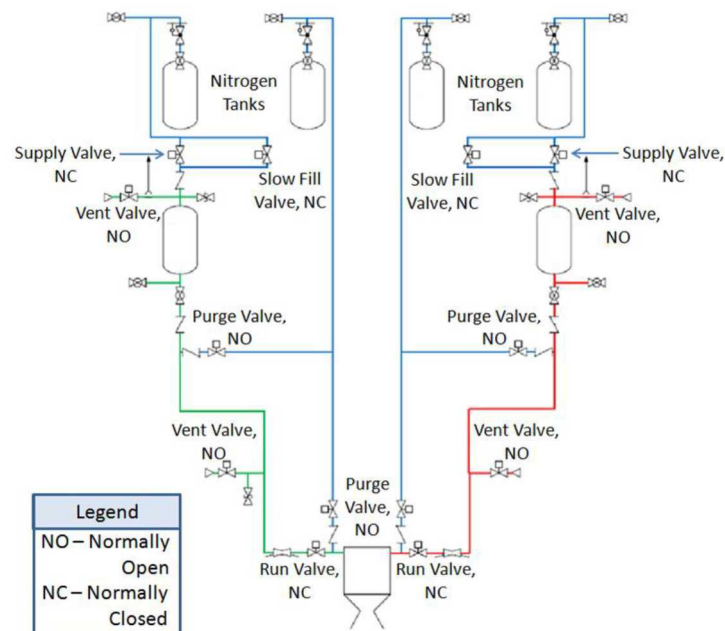
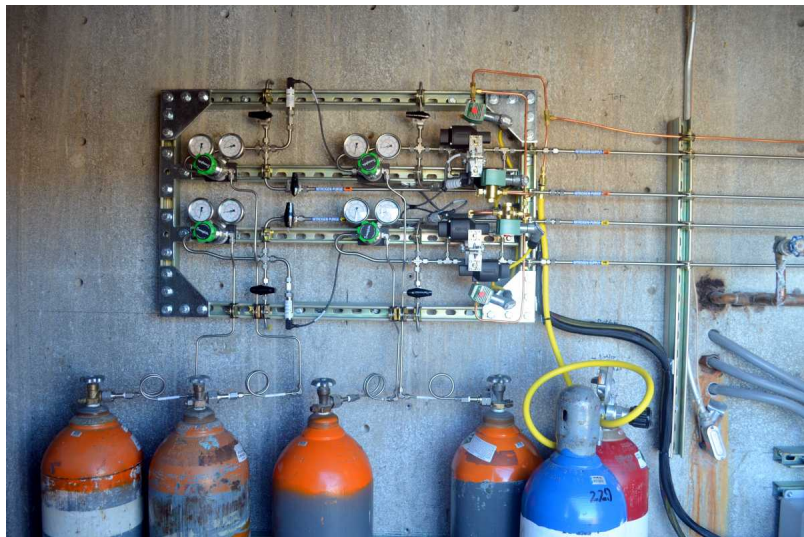


Figure 4: Simplified schematic of propellant supply system detailing valve function and operation

Pneumatically actuated valves are used to control propellant flow. The valve's unpowered state (normally closed/normally open) operation was selected so the system vents all propellants and pressure automatically from the system during emergency shut down situations or power loss. In the event of an emergency, including full-system power loss, the system is purged and put into a safe state simply by removing power to the valves.

The system is constructed using Swagelok stainless steel fittings and 304 stainless steel tubing in order to allow a variety of propellants to be implemented without concern for corrosion or material incompatibility. The use of Swagelok components also permits reconfiguration and modifications to the system with off the shelf components. The oxidizer side of the system is oxygen cleaned in accordance with Compressed Gas Association (CGA) requirements with custom parts cleaned at. The system is limited to a maximum allowable working pressure (MAWP) of 12.4MPa (1800psi), which is established by the stainless steel sample cylinders used as propellant tanks. For safety, pressure relief valves are incorporated on both sides of the supply system in addition to burst disks rated for 12.4Mpa (1800psi) +/-0.69MPa (100psi).

The propellant supply system is divided into three main sections: the nitrogen supply panel, the propellant run tank panel, and the rocket engine connection hardware. Figure 5 shows the installed nitrogen supply panel.



*Figure 5: Installed nitrogen supply panel*

The nitrogen supply panel consists of four regulators which allow supply and purge pressures to be individually set for the fuel and oxidizer sides of the system. The panel is designed to be supplied by four 41.4MPa (6000psi), high pressure nitrogen gas cylinders, and the regulators are rated to provide up to 20.7MPa (3000psi) although the system is limited to 12.4MPa (1800psi) at this time.. A slow pressurization system is incorporated on both the fuel and oxidizer supply sides to prevent rapid adiabatic compression of the propellants in the supply tanks.

Figure 6 shows the installed run tank panel. The propellant run tank panel consists of two 3.78L (1 gal) double-ended sample cylinders manufactured by Swagelok. Each run tank is instrumented for tank pressure and temperature and is equipped with a burst disk and a pressure relief valve located at

the top of the cylinder. The pressure and temperature monitoring is vital during the filling operations, with nitrous oxide to ensure that the nitrous oxide does not reach a temperature that could lead to decomposition [9]. These temperature and pressure measurements are used to determine the flow rate of each propellant through the cavitating venturis.



*Figure 6: Installed propellant run tank panel*

Filling of the system with propellants is handled remotely to minimize operator exposure. Remotely operated pumps are used to transfer the ethanol and nitrous oxide into their respective tanks. The nitrous oxide is stored in a bulk nitrous oxide cylinder that is inverted to allow the liquid nitrous oxide to be drawn from the cylinder. The nitrous oxide source cylinder and ethanol supply tank are mounted on load cells, allowing the mass loaded into the run tanks to be determined remotely. Figure 7 shows a view of the final connections made to the rocket engine. The exhaust nozzle is on the left side of the image, with two lenses from the schlieren optical diagnostic system visible in front of and behind the engine. The igniter is located on top head end of the rocket engine. The fuel and oxidizer are injected into the propellant manifold section from the front and back sides of the engine in the image, respectively.

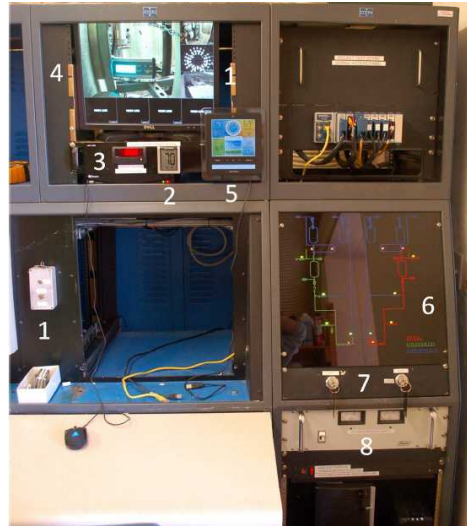


*Figure 7: Side view of installed rocket engine and rocket engine connections*

### **Control System**

A National Instruments (NI) based system is used as a control system and for data acquisition. The NI hardware interfaces to the computer command console uses NI's LabVIEW software. A NI cDAQ-9188 permits interfacing with up to eight data processing and control modules. System pressure is monitored through an eight channel NI9203 current sensing analog measurement module capable of up to 200,000 samples per second for a single channel. Transducers Direct, 20ma current pressure transducers are connected to this module for all system pressures. Temperature measurements are made using Type-K thermocouples connected to a sixteen channel, NI 9213 thermocouple analog sensing module capable of 75 samples per second per channel. Engine thrust is measured using an Interface Force WMC-500 load cell, paired with a four channel NI 9237 full bridge transducer module capable of 50,000 samples per second per channel.

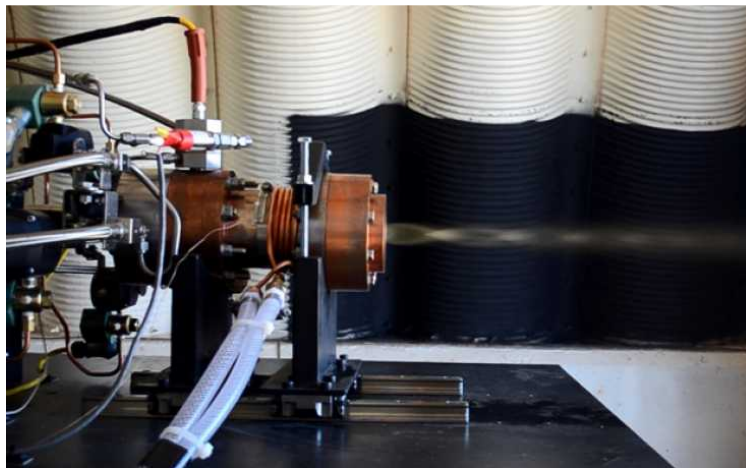
The LabVIEW displays system pressures and temperatures and permits variable and automated timed valve actuation for rocket engine operation as well as manual override control of individual valves, while providing real time data acquisition. Figure 8 shows the control console utilized for operations at REF.



*Figure 8: Console for operations and site monitoring. Visible are: Deadman's switch (1); Fuel galley temperature monitoring (2); Igniter supply voltage (3); Video observation system (4); Weather station (5); Valve status indicator panel (6); Propellant loading controls (7); and system power (8).*

### **Experimental Results**

The first successful test firing of the rocket engine at REF took place on March 25, 2015. In total, nine test firings have been conducted using liquid nitrous oxide and ethanol as the propellants. Figure 9 shows the steady state operation of the rocket engine during a test.



*Figure 9: Steady-state rocket engine operation during Test 5/29/2015  
External cooling loop visible for rapid engine cool down between tests.*

Figures 10 and 11 show the plotted engine performance for Tests 5/29 and 6/2, respectively, with the measured performance for Tests 5/29 and 6/2 summarized in Table 1. The minor overshoot in chamber pressure is an artifact of the pressure transducer port measuring igniter pressure until the igniter is shut down.

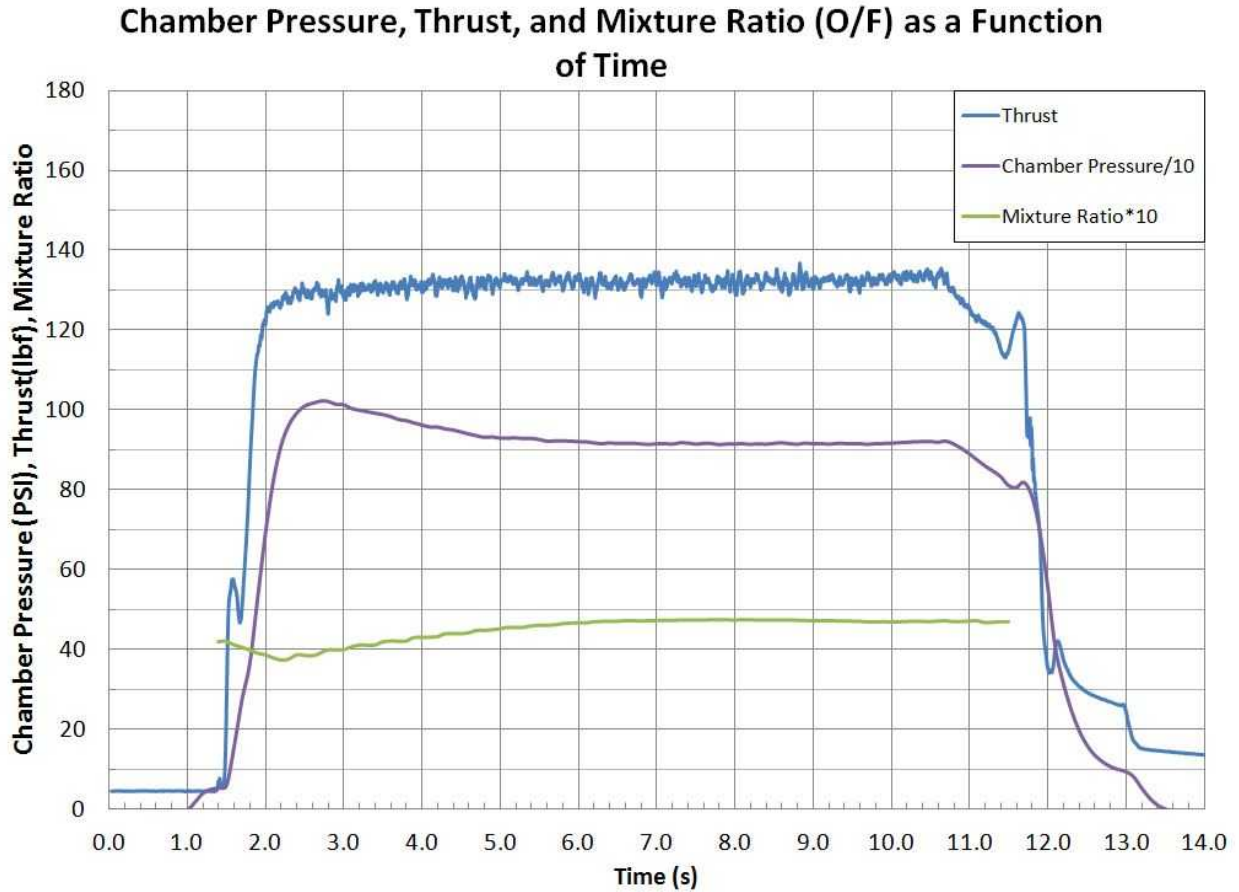


Figure 10: Rocket engine performance for Test 5/29. Chamber pressure, thrust, and mixture ratio are  $p$  as a function of time. The average steady-state flow rates were 0.190kg/s (0.419lbm/s) of nitrous oxide and 0.040kg/s (0.089lbm/s) of ethanol. The average mixture ratio was 4.71.

### Chamber Pressure, Thrust, and Mixture Ratio (O/F) as a Function of Time

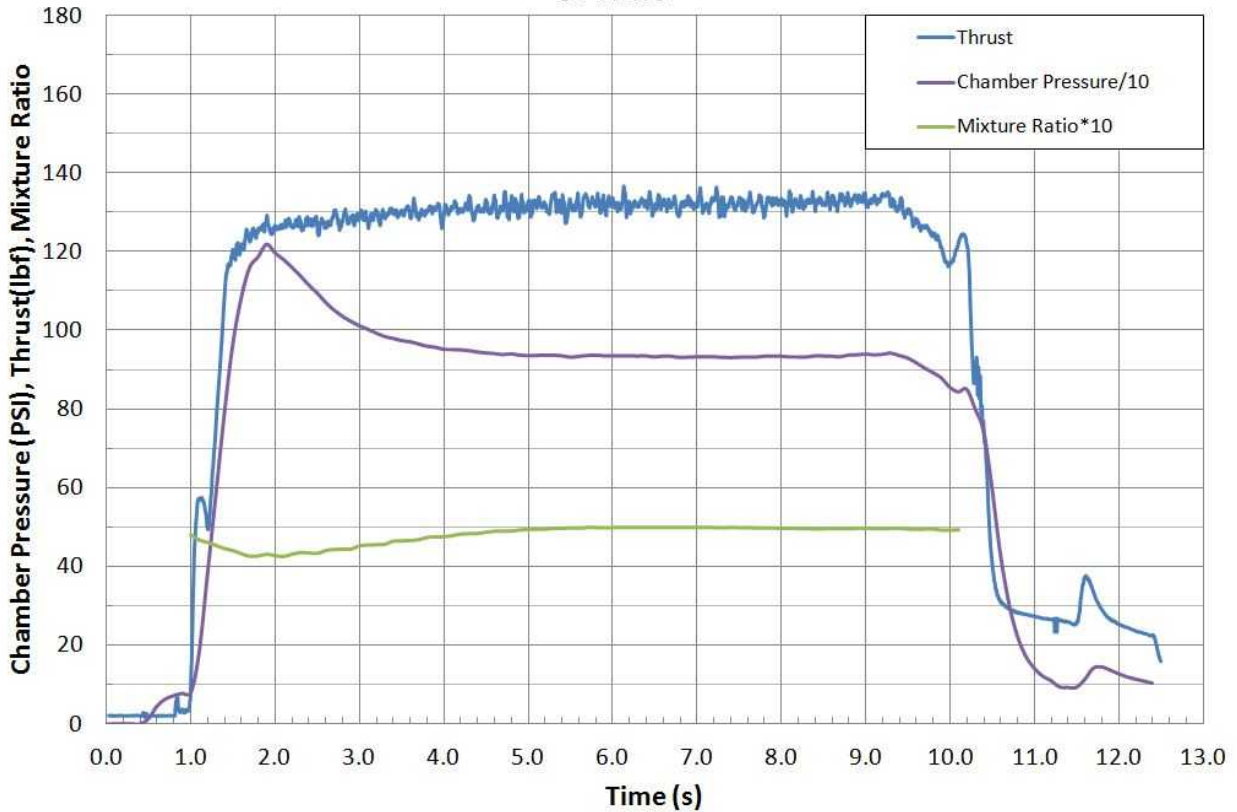


Figure 11: Plotted rocket engine performance for Test 6/2. Chamber pressure, thrust, and mixture ratio are plotted as a function of time. The average steady-state flow rates were 0.200kg/s (0.442lbm/s) of nitrous oxide and 0.040kg/s (0.089lbm/s) of ethanol. The average mixture ratio was 4.97.

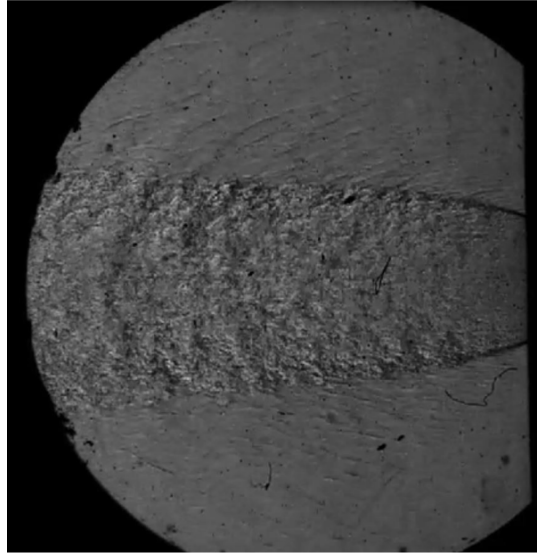
Table 1: Experimental engine performance result summary for Test 5/29 and Test 6/2

Test	Calculated Flow Rate	MR	Chamber Pressure	Thrust	Isp
Units	kg/s (lbm/s)		Mpa (psi)	Nt (lbf)	Nt·s/kg (lbf·s/lbm)
Uncertainty	±0.004 (±0.008)	±0.2	±0.06 (±8)	±4 (±0.8)	±49 (±5)
5/29	0.230 (0.508)	4.71	6.32 (917)	592 (133.2)	2569 (262)
6/2	0.241 (0.532)	4.97	6.44 (935)	590 (132.6)	2461 (251)

The calculated specific impulses for Tests 5/29 and 6/2 were close to the value theoretical values calculated by the NASA CEA code of 2599 Nt·s/kg (265 lbf·s/lbm) for both run conditions. These two tests demonstrated successful operation of the REF and generated initial performance data for nitrous oxide and ethanol.

High-speed schlieren imaging was conducted during these tests to image the engine exhaust plume. The schlieren imaging demonstrated that the flow was approximately perfectly expanded

through the nozzle, indicating the test was performing near design conditions. In the future, these schlieren images will be combined with a seedless schlieren image velocimetry technique [14] to measure velocities in the nozzle flow field. Figure 12 shows an image of a high-speed schlieren image series of exhaust flow exiting the nozzle.



*Figure 12: High-speed schlieren imaging of nozzle exhaust flow during steady state operation*

### **Conclusion**

This work was conducted through a collaborative effort between Sandia National Laboratories and NMIMT. NMIMT developed a test facility with capabilities to support bi-propellant rocket engine development and testing. Nitrous oxide and ethanol was successfully test fired in a bi-propellant rocket engine that delivered a specific impulse in the range of 2452 to 2550 N·s/kg (250 to 260 lb<sub>f</sub>-sec/lb<sub>m</sub>). These preliminary results of nitrous oxide and ethanol testing support further investigation of the propellant combination to evaluate the operational envelope and suitability as a green propellant combination for both engine and gas generator use.

The establishment of the REF at EMERTC provides for future research capabilities in engine and propellant development, and the development of diagnostic techniques including flow visualization and plume analysis. Most importantly, the REF provides a teaching tool for both graduate and undergraduate propulsion engineers at NMIMT.

### **Future Research**

Future research at REF will include the expansion of rocket engine performance evaluation tools as well as continued testing of nitrous oxide and ethanol as potential rocket engine and gas generator propellants. Future performance evaluation tools will include the expansion of the data acquisition system at the facility to provide additional engine instrumentation capabilities. This will include the addition of capabilities for exhaust temperature measurements as well as temperature measurements along the engine to measure heat flux from the chamber and nozzle in order to determine thermal losses and develop a fuel based regenerative cooling system. High speed optical analysis of the exhaust plume will also be further developed. This will include integration of seedless schlieren image

velocimetry and focusing schlieren [14] to permit interior analysis of the exhaust plume and optical velocity measurement.

Future propellant evaluation of nitrous oxide and ethanol will include testing of neat ethanol and nitrous oxide as propellants over a range of chamber pressures and mixture ratios and ethanol-water mixtures to determine ignitability limits of diluted ethanol as a fuel. As a result of previous academic work [15] anhydrous ammonia will be evaluated as a potential clean burning gas generator fuel with nitrous oxide.

### Acknowledgement

This research is supported at NMIMT through Sandia PO 1415058.

### References

1. Vadim Zakirov, Martin Sweeting, Timothy Lawrence, and Jerry Sellers. *Nitrous Oxide as a Rocket Propellant*. Acta Astronautica, 48(5-12):pp 353–362, 2001.
2. Chung K. Law. *Fuel Options for Next-Generation Chemical Propulsion*. AIAA, 50(1):pp. 19–36, January 2012.
3. Mark Grubelich, John Rowland, and Larry Reese. *A Hybrid Rocket Engine Design for Simple Low Cost Sounding Rocket Use*. AIAA 29th Joint Propulsion Conference and Exhibit, June 1993.
4. Benjamin S. Waxman, Jonah E. Zimmerman, Drian J. Cantwell, and Gregory G. Zilliac. *Effects of Injector Design on Combustion Stability in Hybrid Rocket Using Self-Pressurizing Oxidizers*. 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2014.
5. Shinichiro Tokudome, Tsuyoshi Yagashita, Ken Goto, Hiroto Habu, Naohiro Suzuki, Fuyuko Fukuyoshi, Yasuhiro Daimoh, and Fumio Okuno. *Experimental Study of Nitrous Oxide/Ethanol Propulsion System: Technology demonstration with a bbm*. European Conference for Aeronautics and Space Sciences 2013 Meeting, July 2013.
6. Arie Peretz, Omry Einav, Ben-Ami Hashmonay, Avi Birnholz, and Zeev Sobe. *Development of Laboratory-Scale Hybrid Engine Test Facility*. Propulsion and Power, 27(1):pp. 190–196, 2011.
7. David Helderma. *Measurement and Analysis in a Subscale Rocket Combustor*. Master's thesis, Purdue University, 2009.
8. Benjamin S. Waxman, Jonah E. Zimmerman, Drian J. Cantwell, and Gregory G. Zilliac. *Effects of Injector Design on Combustion Stability in Hybrid Rocket Using Self-Pressurizing Oxidizers*. 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2014.

9. Stewart Youngblood. *Design and Testing of a Liquid Nitrous Oxide and Ethanol Fueled Rocket Engine*. Master's thesis, New Mexico Institute of Mining and Technology, 2009.
10. Zola Fox. *Cavitating Venturis for Small Pulsing Rocket Engines*. *Space/Aeronautics*, 38(7), December 1962.
11. George A. Repas. *Hydrogen-Oxygen Torch Ignitor*. Technical report, NASA, March 1994.
12. George P. Sutton and O. B. Oscar Biblarz. *Rocket Propulsion Elements*. Wiley and Sons, 7th edition, 2001.
13. Compressed Gas Association. *CGA g-4.1: Cleaning equipment for oxygen service*, 1985.
14. Michael J. Hargather, Michael J. Lawson, Gary S. Settles, Leonard M. Weinstein, Sivaram Gogineni. *Focusing-Schlieren PIV Measurements of a Supersonic Turbulent Boundary Layer*. 47th AIAA Aerospace Sciences meeting. January 2009.
15. J.D. Lindholm. *Analysis of Nitrous Oxide as a Propellant with Selected Fuels*. Master's thesis, New Mexico Institute of Mining and Technology, 2013.